

## Article by Alexander Graham Bell, undated

### **Rough Draft UPON THE TETRAHEDRAL PRINCIPLE IN KITE CONSTRUCTION.**

A few years ago I made a communication to the Academy upon the subject of “Radial-Winged Kites”; and some of the photographs shown to the Academy at that time were afterwards published in the Monthly Weather Review. Since then I have been continuously at work upon experiments relating to kites — why I do not know — excepting perhaps because of the intimate connection of the subject with the flying machine problem.

We are all of us interested in aerial locomotion and I have had the feeling that a properly constructed flying machine should be capable of being flown as a kite; and — conversely — that a properly constructed kite should be capable of use as a flying machine when driven by its own propellers.

The applicability of kite experiments to the flying machine problem has at all events for a long time past been my guiding idea. I have not cared to ascertain how high a kite may be flown — or to make one that should fly at any great altitude. The point I have had specially in mind is, that the equilibrium of the structure in the air should be perfect — that it the kite should fly steadily and not move about like an imprisoned bear — and that when released it should drop slowly and gently to the ground without material oscillation. I have also considered it important that the framework should possess great strength with little weight. I believe that in the form of structure now attained the properties of strength, lightness and steady flight have been united in a remarkable degree.

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In my younger days the word “Kite” suggested a structure of wood in the form of a cross covered with paper — making a diamond-shape surface longer one way than the other

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—provided with a long tail composed of a string with numerous pieces of paper tied at intervals upon it. The whole flown by a bridle somewhat as in the following illustration:

Such a kite is a toy; and in Europe and in America, where kites of this type prevailed, kite flying was pursued only as an amusement for children and the improvement of the form of structure was hardly considered a suitable subject of thought for a scientific man. In Asia, kite flying has been for hundreds of years, the amusement of adults and the Chinese, Japanese, and Malays developed tailless kites very much superior to any form of kite known to us. It is astonishing how little was known in Europe or America of the admirable and ingenious kites used by Asiatics, and I presume that our lack of interest in the subject arose from the false idea that a kite could only be a plaything or toy of no practical use to anybody.

It is only within quite recent times that improvements in kite structure have been seriously considered, and the recent developments in this art have been mainly due to one man, Mr. Laurence Hargrave of New South Wales Australia. . Hargrave realized that the structure best adapted for what is called a good kite would also be suitable as the basis for the structure of a flying machine. His researches published by the Royal Society of New South Wales have attracted the attention of the world, and form the starting point for modern researches upon the subject in Europe and America. Anything relating to aerial locomotion has an interest to very many minds; and scientific kite flying has everywhere been stimulated by Hargrave's experiments. In America however, the chief stimulus to scientific kite flying has been the fact developed by the United States Weather Bureau, that important information could be obtained concerning weather conditions if kites could be constructed capable of lifting meteorological instruments to a great elevation in the free air. Eddy and others in America seemed to have taken the Malay tailless kite as a basis for their experiments; but Professor Marvin of the U. S. Weather Bureau , and Dr. Rotche of the Blue Hill Observatory and many others have taken Hargrave's box kite as a basis. Congress made an appropriation to the Weather Bureau in aid of its kite experiments and a number of meteor o logical stations throughout the United States have been equipped

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with the Marvin kite. Continuous meteorological observations at a great elevation have been taken at the Blue Hill Observatory; and Dr. Rotche has demonstrated the possibility of towing kites at sea by means of 4 steam vessels so as to secure a continuous line of observation s all the way across the Atlantic.

Hargrave introduced what is known as the cellular construction of kite. H e constructed kites compose d of many cells, but found no substantial improvement in many cells over two alone; and a kite composed of two rectangular cells separated by a considerable space is now universally known as the Hargrave box kite. This represents in my opinion, the high water mark of progress in the nineteenth century; and this form of kite forms the starting point for my own researches.

The two cells are on the same horizontal level — one constituting the front cell of the kite, the other the rear. They are connected together by a framework so that a considerable space is left between the fore and aft cells. This space is the most essential/feature of the kite: Upon it depends the fore and aft stability of the kite. The greater the space — the more stable is the equilibrium of the kite in a fore and aft direction — the more it tends to assume a horizontal position — and the less it tends to dive or pitch.

Each cell is provided with vertical sides; and these again seem to be essential elements of the kite contributing to lateral stability. The greater the extent of the vertical sides — the greater the stability in the lateral direction — and the less tendency has the kite to roll, or move from side to side — or turn over in the air. The following is a drawing of a typical form of Hargrave kite:

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In the above drawing of a Hargrave box kite I have shown only necessary details — with only sufficient framework to hold the cells together.

It is obvious that such a kite is of very flimsy construction: It requires additions to the framework of various sorts to give it sufficient strength to hold the supporting surfaces

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in their proper relative positions and prevent distortion or bending, or twisting of the kite-frame under the action of the wind. Unfortunately, the additions required to give rigidity to the framework, detract from the efficiency of the kite:— First by rendering the kite heavier so that the ratio of weight to surface is increased; and secondly by increasing its head resistance by interior bracing. The interior bracing advisable, in order to preserve the cells from distortion, comes in the way of the wind — thus adding to the drift of the kite without contributing to the lift.

A rectangular cell is structurally weak — as can readily be demonstrated by the little force required to distort the cell A into the form shown at B:

In order to remedy this weakness, internal bracing is advisable of the character shown below:

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This internal bracing — even if made of the finest wire so as to be insignificant in weight — all comes in the way of the wind, increasing the head resistance of the kite without any counterbalancing advantage.

In looking back over the line of experiments in my own laboratory, I recognize that the adoption of a triangular cell was a step in advance — constituting indeed one of the milestones of progress — one of the points that stand out clearly against the hazy background of multitudinous details. The following is a drawing of a typical triangular celled kite upon the same general model as the typical Hargrave kite shown before.

A triangular frame is by its very structure, perfectly braced in the direction of its own place, so that internal bracing of any character is unnecessary to prevent distortion of a kind analagous to that referred to above in the case of the Hargrave rectangular cell.

While the lifting power of such a triangular cell is probably less than that of the ordinary Hargrave cell, the enormous gain in structural strength, together with the reduction of

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head-resistance and weight, due to the omission of internal bracing, counterbalance any possible deficiency in this respect. While theoretically the triangular cell is inferior in lifting power to Hargrave's four-sided rectangular cell — practically there is no substantial difference. So far as I can judge from observation in the field, kites constructed on the same general model as the Hargrave, but with triangular cells instead of quadrangular, seem to fly as well as the ordinary Hargrave form, and at as high an angle.

Such kites are therefore superior:— For they fly substantially as well, while at the same time they are stronger in construction, lighter in weight and offer less head-resistance to the wind.

Triangular cells are also admirably adapted for combining together into a compound structure of any size in which the surfaces do not interfere with one another. For example, three triangular celled kites tied together at the corners form a compound cellular kite as shown below:

Such a compound kite flies as well as the individual kites of which it is composed. The weight of the compound kite is the sum of the weights of the three kites of which it is composed and the total surface exposed is just three times the surface of one of the individual kites. It is obvious in such a construction that the doubling of the longitudinal sticks where two corners come together is an unnecessary feature of the combination, and that one stick could be substituted with advantage for the two, so that in this case the weight of the compound kite may be less than the sum of the weights of the component kites, while the surface is the same.— In compound kites of this character therefore, the ratio of weight to surface diminishes with every increase in the dimensions of the kite; and the larger kites have less weight in proportion to their surfaces than the smaller ones of which they are composed. This disposes altogether of the general conclusion reached by Professor Simon Newcomb in an article published in McClures Magazine for September 1901, entitled "Is the Airship coming" namely that "The construction of an aerial

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vehicle which could carry even a single man from place to place at pleasure, requires the discovery of some new metal, or some new force”.

The process of reasoning, by which Professor Newcomb arrived at this remarkable result is undoubtedly correct, although his conclusion is only partially true, because he has drawn a general conclusion from restricted premises. He says:”

“Let us make two flying machines exactly alike, only make one on double the scale of the other in all its dimensions. We all know that the volume, and therefore the weight of two similar bodies are proportional to the cubes of their dimensions. The cube of two is eight. Hence the large machine will have eight times the weight of the other. But surfaces are as the squares of the dimensions. The square of two is four. The heavier machine will therefore expose only four times the wing surface to the air, and so will have a distinct disadvantage in the ratio of efficiency to weight.”

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He shows that where two flying machines — or I may add kites — are “ exactly alike ” differing only in the scale of their dimensions, the ratio of weight to supporting surface is greater in the larger than in the smaller, and increases with the increase in dimensions, so that given a structure large enough it would be too heavy to fly. the supporting surface would increase as the square, but the weight of the cube of the dimensions, the supporting surface would increase as the square, but the weight of the cube of the dimensions, This is undoubtedly true and accounts for my failure to make a giant kite upon the Hargrave model that should lift a man. When the kite was constructed with two cells each about the size of a small room it was found that it would take a hurricane to raise it in the air. It proved to be not/only incompetent to carry of a load equivalent to the weight of a man, but could not even raise itself in an ordinary breeze in which smaller kites upon the same model flew perfectly well. the supporting surface would increased the square, but the weight or the cube of the dimensions.

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But Professor Newcomb's results are only true when restricted to his premises. The large machine will be heavier in proportion to its surface where the smaller where the two models are "exactly alike", only differing in the scale of their dimensions. The general conclusion that the construction of an aerial vehicle of any sort that could carry a man is impossible, with out the discovery of some new metal or some new force, is not warranted because it goes beyond the premises with which he started.

My own experiments with cellular kites composed of triangular cells connected corner to corner have amply demonstrated the fact that the size of a compound kite may be increased indefinitely, without increasing the ratio of weight to supporting surface, and that the compound structures fly in 10 as light a breeze as the smaller kites of which they are compounded.

While kites with triangular cells are structurally strong in a transverse direction, they are structurally weak in the longitudinal direction, requiring diagonal bracing to prevent bending or twisting under the action of the wind.

The necessary bracing however — not being in the way of the wind —does not materially affect the head-resistance, and is only disadvantageous by adding dead-load, thus increasing the ratio of weight to surface.

Passing over in silence multitudinous details of experiments in kite construction I come to another conspicuous point of advance —another milestone of progress — the adoption of the triangular construction in every direction — longitudinally as well as transversely; and the clear realization of the fundamental importance of the skeleton of a tetrahedron — especially the regular tetrahedron — as an element of the structure or framework of a kite or flying machine. A tetrahedron is a form of solid bounded by four triangular surfaces. In the regular tetrahedron the boundaries consist of four equal equilateral triangles. The regular tetrahedron thus has four equal triangular faces, and six equal edges. In the skeleton form, the edges alone are represented; and the skeleton of the a regular 11

tetrahedron is produced by joining together six equal rods end to end so as to form four equilateral triangles.

One of the common puzzles for the amusement of children, — and adults too for that matter, — is the following: — take six matches and with them form four complete triangles (equilateral triangles). The difficulty lies in the unconscious assumption of the experimenter that these four triangles should be all in the same plane, so that he tries to form them by laying the matches down on the table in front of him, and arranging them in various ways. The moment he realizes that the triangles need not be in the same plane, the solution of the problem comes easy: — Place three matches on the table, so as to form a triangle, and stand the other three up over this like the three legs of a tripod stand.

The matches then form the skeleton of a regular tetrahedron.

A framework formed upon this model of six equal rods fastened together at the ends constitutes a structure possessing the qualities of strength and lightness in an extraordinary degree. It is not simply braced in two directions in space like a triangle, but in three directions like a solid. If I may coin a word, it possesses “three-dimensional strength” — not two — dimensional-strength like a triangle, or one-dimensional-strength like a rod. It is the skeleton of a solid, not of a surface or a line.

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It is astonishing how solid such a framework appears even when composed even of very light and fragile material; and compound structures formed by fastening these tetrahedral frames together at the corners so as to form the skeleton of a regular tetrahedron on a larger scale, possess equal solidity.

The equilateral tetra-triangular frame — as an element of kite structure — seems to me to be the most important point yet developed. Just as you can build houses of all kinds out of bricks, so you can build kite structures of almost any form, out of these tetrahedral cells,

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and the whole structure will possess the same qualities of solidity and lightness possessed by the individual cell.

Of course the use of such a cell is not limited to the construction of the framework for a kite or a flying machine, but it is applicable to any kind of structure whatever in which it is desirable to combine strength and lightness. I have already built a house — a framework for a giant windbreak — three or four boats — as/well as several forms of kites out of these elements, photographs of which may be found in the volume of illustrations which I submit for the inspection of the members of the Academy. The model structure before you composed of small tetrahedrons made of brass wire illustrates the mode of construction used in the framework of the giant windbreak, a photograph of which you have before you, and used also in the kites which I have termed “winged-boats”, which have demonstrated their lifting power — unintentionally — by lifting men off their feet. In one experiment a young man was carried up into the air accidentally about four feet before he let go, and in another experiment two men were 13 raised in a similar manner so that we have learnt by experience to respect the lifting powers of these kites; and further experiments with them have been postponed until the trials can be made over water to diminish the danger of accident.

One of the photographs placed in your hands shows a form of kite carrying on its under surface three boats side by side, — in catamaran style, the framework of these boats being composes of tetrahedral cells. The central boat is of strong material as it is designed to support the weight of a man and engine. The side boats are of lighter material as they are designed to act merely as floats to prevent the apparatus from upsetting on the water. One of the photographs shows this kite actually floating upon the water, with a man standing upon the central boat.

The tetrahedral principle enables us to construct a solid framework for a kite of very light material admirably adapted for the support of aeroplanes or surfaces of any kind — for example aerocurves.— The best arrangement of surfaces/has not yet been experimentally

determined, but I beg to submit to the Academy a form of kite in which all the surfaces are oblique, and which flies with such remarkable steadiness as to show that horizontal surfaces are not necessary in a good flying kite — however even if advisable. The framework consists of four tetrahedral frames connected together at the corners so as to form a compound structure which has itself the form of the regular tetrahedron.

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Each tetrahedral cell is covered on two of its sides by silk, thus carrying two triangular aeroplanes at an angle of sixty degrees to one another, so that when it is placed upon one edge it resembles a pair of birds wings connected above at the tips by a horizontal cross-bar. The tetrahedral kite formed of four of these elements is shown below:

This kite flies very steadily with a cord attached to its bow as in the illustration.

When four of these tetrahedral kites are connected together as shown in the next illustration, the compound kite framework forms the skeleton of a regular tetrahedron on a large r scale:

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This kite also flies very steadily when flown by a cord attached to the bow and when the position of the cord is shifted along the keel towards the center of the kite, the angle of flight is increased until it flies nearly towards the zenith, but it is not advisable to make the point of attachment as far back as the middle of the keel. About half way between the bow and the middle of the keel is a point where good results will be obtained.

Four of these compound tetrahedral kites connected at the corners form the skeleton of a regular tetrahedron upon a still larger scale. I see no reason to doubt that this form of kite can be increased indefinitely in size. So far as my experiments show — the larger compounds are more reliable and steady in their flight than the smaller.

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It is not my object in this communication to attempt a description of the multitudinous experiments carried on in my Nova Scotia laboratory, but simply to bring to your attention, the importance of the tetrahedral principle in kite construction.